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13. ABSTRACT (Maximum 200 words)

The aim of this work was to test and validate a new approach to quantitatively analyze well hydrographs in shallow, fractured and karstic aquifers. This approach was demonstrated to be reliable, and estimates of transmissivity (T) and specific yields (Sy) in different portions of a flow regime can be obtained by the use of this less costly, non-invasive, passive method.

Under the ARO funded project, field work included collecting hydrograph data and conducting aquifer testing at selected wells at the Crane, IN, the Y-12, TN, and the Fort Campbell, KY sites. Evaluation of the results indicates that the hydrograph analysis method produces results of aquifer parameter estimates (matrix T) of comparable reliability to those obtained using conventional aquifer testing techniques. Hydrograph analysis results differ from those of slug tests in cases where cavities are located in the well's completion zone. This results because the slug test results are biased toward the high conductivity, near well-bore conduits, whereas the hydrograph method evaluates matrix T. Using sensitivity and statistical analyses, ongoing work is directed toward assessing the various conditions under which this method is applicable and reliable, and under which site conditions it is less reliable.

14. SUBJECT TERMS
hydrogeology, groundwater, aquifer parameters, transmissivity, karst

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Final Report

On the ARO Sponsored Project

Use of Well Hydrographs in Shallow Fractured Aquifers to Determine Specific Yields and Transmissivities

Grant Number: DAAH04-96-1-0392

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1. Foreword (optional)

The aim of this work was to test and validate a new approach to quantitatively analyze well hydrographs in shallow, fractured and karstic aquifers. This approach was demonstrated to be reliable, and estimates of transmissivity (T) and specific yields (S_y) in different portions of a flow regime can be obtained by the use of this less costly, non-invasive, passive method.

Under the ARO funded project, field work included collecting hydrograph data and conducting aquifer testing at selected wells at three sites: the Ammunition Burning Ground in Crane, IN; the Y-12 Plant in Oak Ridge, TN, and the Main Cantonment area of Fort Campbell, KY. The results of this work indicate that the hydrograph analysis method produces aquifer parameter estimates (matrix T) of comparable reliability to those obtained using conventional aquifer testing techniques. Hydrograph analysis results differ from those of slug tests in cases where cavities are located in the well's completion zone. This results because the slug test results are biased toward the higher conductivity, near well-bore conduits, whereas the hydrograph method evaluates the lower conductivity, matrix T.

2. Table of Contents

3. List of Appendixes, Illustrations and Tables

4. Statement of the Problem

Numerous Army facilities have historically conducted activities that have contaminated groundwater with both organic and inorganic materials. In order to properly manage these sites, aquifer parameters must be obtained for adequate characterization and predictive modeling to be conducted. Some of these sites are located in karst aquifers, which was the focus of this work. If the technique being developed here could be demonstrated to be reliable at these karst sites, more reliable aquifer information could be obtained at a reduced cost, thus decreasing the overall cost of characterizing and remediating groundwaters at Army facilities.

Army sites are not the only areas in which groundwater has been contaminated by past or current activities. Many other DoD and DOE facilities, as well as privately owned properties, have contaminated groundwater systems requiring characterization and remediation. Many of these sites are also located in karst terrains, and hence, the hydrograph analysis method could provide more reliable data at a reduced cost for the site facilities management and their consultants.

Analytical techniques are well developed for hydrographs obtained from streams and springs, where data are cast in terms of total discharge. In contrast, well hydrographs are plots of water level versus time. It was hypothesized that three segments on a recession curve from wells in a fractured or karst aquifer (multiple porosity systems) represent drainage from three types of storage: conduit or larger fractures, smaller fractures, and matrix. A method was developed to estimate matrix transmissivity (T) and specific yields (S_y) in these different components of the aquifer using well hydrograph data.

Prior to this funded work, the well hydrograph analysis method had only been applied to a limited extent at one site, and application and refinements at other fractured or karst sites were needed to determine if the method could be more universally applicable as a standard analysis tool in other shallow, fractured (multiple porosity) aquifers. The main benefits of this method are in the acquisition of matrix T and S_y values for multiple components of a fractured system rather than solely for the continuum as is determined from more traditional aquifer tests. In addition, the method involves passive monitoring of a well bore, which is desirable in contaminated areas because typical well testing requires pumping water out of the borehole. Containment and treatment of the pumped waste water are costly, and use of the hydrograph analysis method results in avoidance of these costs. Hence, if the hydrograph method could be demonstrated to be applicable at other sites, additional information on aquifer parameters could be obtained at a reduced cost.

The shape of the rising limb of a hydrograph is largely dictated by the characteristics of a storm event, whereas the shape of the recession limb is largely independent of the character of the storm (Linsley et al., 1982). Recession limb analysis often leads to two or more line segments that represent responses in the different portions of the ground-water system: (1) a fast response to conduit or fracture flow; (2) slower responses due to flow through smaller fracture networks and unfractured porous media (White, 1988). At relatively shallow depths (<50 m) in areas with sufficient precipitation, rapid water level responses are expected in conduits and fractures, in contrast to slower responses in the more diffuse portions of the aquifer. Because fractured and conduit systems have little hydraulic resistance in contrast to porous media, recharged water is expected to drain quickly. The porous media part of the system has much lower hydraulic conductivity and responds more slowly to transient events.

Relatively few studies (Atkinson, 1977; Rorabaugh, 1960) have yielded quantitative data on aquifer parameters using well hydrographs. It has been previously noted that stream flow recession curves can be approximated by three straight lines on a semilogarithmic plot, with the lines representing three different types of storage: stream channels, surface soil, and groundwater (Barnes, 1940; Linsley et al., 1982). Work has been conducted using well hydrographs in the karst, Cambrian Maynardville Limestone at the Y-12 Plant in Oak Ridge, Tennessee. Shevenell (1996) hypothesized that three segments on a recession curve from wells in a karst or fractured aquifer also represent three types of storage: larger fractures or conduits, smaller fractures, and matrix portions of the aquifer.

The purpose of the ARO funded work was to test, validate and refine the scheme to quantitatively analyze well hydrographs in shallow, fractured rock and karstic aquifers. If this scheme could be demonstrated to be reliable at other sites, estimates of transmissivity and specific yield in different portions of the flow regime could be obtained by use of an inexpensive, non-invasive method that does not disturb the aquifer.

5. Summary of the Most Important Results

Results based on field observations and theoretical considerations show water level variations in wells in response to storm events are similar to those monitored in springs discharging in karst aquifers. Methods have long been used to analyze spring hydrograph recession curves, and the work presented here suggests these methods can be extended to analyze the similar well hydrograph recessions. In this work, hydrograph analysis results, which provide an estimation of T in matrix intervals, were compared to results obtained from traditional aquifer testing methods.

Table 1 lists all of the wells monitored and evaluated as part of the funded project. The hydrograph analysis method could only be tested against a relatively small number of results obtained from pumping tests. During this study, no wells could be pumped at the Crane site, only one could be pumped at the Ft. Campbell site, yet several wells at the Y-12 site could be pumped. However, at all three sites numerous wells were tested with the use of hydrographs, which do not require withdrawal of ground water, and this is precisely one of the main reasons to investigate the non-invasive hydrograph method.

Table 2 summarizes results of the estimation of aquifer T at all three sites. Arithmetic means were computed at individual wells in cases where there were multiple T estimates for the well. Geometric mean values were computed when averaging T from multiple well locations because this parameter is usually considered to be spatially log-normally distributed. At all three sites, results of the hydrograph analysis technique closely match (within an order of magnitude) those of traditional, invasive aquifer parameter estimation techniques (aquifer pumping tests and slug tests conducted in matrix intervals). Slug tests conducted in wells completed in cavities show much higher estimated T values as a result of the larger component of quick flow through conduits relative to matrix intervals (Tables 2 and 3). The fact that differences in T values occur between techniques may be explained by the difference in scale-of-measurement between techniques. For example, slug testing is usually considered a valid indicator test for T within close radial proximity to the tested well, whereas pumping tests provide a T estimate for a larger portion of the aquifer measured radially outward from a well. Hydrograph analysis may provide

aquifer T estimates for a larger area than that of pumping or slug tests, not radially from a well, but upgradient and dependent on the aquifer drainage geometry.

The results of this work support the hypothesis that well hydrographs may be used to quantitatively assess the hydraulic properties of a well-developed, submerged, fractured or karst aquifer. Results from particular wells indicate that the method may be useful in areas that do not contain cavities, but that do have multiple porosities that are drained (e.g., matrix plus varying fracture sizes/porosities). Wells in larger cavities appear to influence the hydrograph T to a higher degree than purely matrix values and this aspect will be evaluated as part of future work.

There are limitations to this methodology. Sharp storm pulses and, hence, well-defined hydrograph recessions with multiple limb slopes are required to make useful quantifications. Complete recessions must occur before the hydrograph is influenced by the next storm. Simplifications in conduit geometry were assumed so that general relationships between aquifer properties could be obtained, although these simplifying assumptions were not incorporated into the quantitative analysis. Instead, quantitative analysis focuses on the concept of karst aquifer storage depletion as a whole based on the work of Rorabaugh (1964), and conduit drainage (independent of specific conduit shape) as recorded by the well hydrograph during periods of storm recession.

The aquifer parameter estimation technique to obtain matrix T presented here is an alternative to the commonly used pumping and slug testing methodologies. This method provides realistic estimates of aquifer parameters without the need of stressing the aquifer, and hence provides information during times of natural flow conditions. The conduit, fracture and matrix portions of the aquifer upgradient of the monitoring point are represented in this technique, providing a better understanding of aquifer behavior than would be obtained using point measurement techniques alone. A similar argument can be made for the case of discharge from a prominent spring. Such hydrographs provide for an understanding of the upgradient aquifer a spring drains by separately accounting for primary and secondary water storage rather than grouping all permeabilities together. The work presented here suggests that the well hydrograph analysis technique could prove useful in multiporosity areas where pumping test data are lacking or where ground waters are contaminated and pumping is either too costly or simply not permitted.

In using this well hydrograph analysis method, commonly collected hydrograph data are used to go beyond conventional, qualitative methods, and begin to quantify some aspects of the karst aquifer. The results presented here from 49 wells at three different karst sites were compared with those of more traditional aquifer testing methods (pumping, slug). What transmissivities mean in any highly heterogeneous aquifer is a contentious. However, at all three sites, the hydrograph T (which estimate matrix T) agree quite well with data obtained from pumping tests from the same wells, or from slug tests in nearby matrix dominated wells (Table 3). What the T from hydrograph, pump or slug test results represent in the context of a karst aquifer is debatable, yet the latter two methods are frequently used now, and the hydrograph data provide the same level of information as other, more traditional methods that stress the aquifer. Use of the well hydrograph technique in determining matrix T, in combination with (1) traditional tracer test results to obtain flow velocities in quick flow portions of the aquifer, (2) slug tests in quick flow dominated portions of the aquifer to estimate T of the conduit/fracture zones, and (3) estimates of the percentage of the aquifer to which to apply the differing S_y values will allow improved characterization of hydrologic parameters in heterogeneous, multiple porosity systems at Army and many other karst sites.

6. List of All Publications and Technical Reports

Peer Reviewed Papers

Powers, J.G., and Shevenell, L., 2000, Evaluating transmissivity estimates from well hydrographs in karst aquifers, Ground Water, v. 38, no. 3, p. 361-369.

McCarthy, J.F., and Shevenell, L., 1998, Processes controlling colloid composition in a fractured and karstic aquifer in eastern Tennessee, USA, Journal of Hydrology, v. 206, no. 3/4, p. 191–218.

McCarthy, J.F., and Shevenell, L., 1998, Obtaining representative groundwater samples in a fractured and karst aquifer, Ground Water, v. 36, no. 2, p. 251–260.

Shevenell, L., and Goldstrand, P.M., 1997, Geochemical and depth controls on microporosity and cavity development in the Maynardville Limestone: Implications for groundwater flow in a karst aquifer, Cave and Karst Science, v. 24, no. 3, p. 127–136.

Goldstrand, P.M., and Shevenell, L.A., 1997, Geologic controls on porosity development in the Maynardville Limestone, Oak Ridge, Tennessee. Environmental Geology, v. 31, no. 3/4, p. 259–269.

Other Articles, Reports

Reply to comment on: "Shevenell, L., and Goldstrand, P.M., 1997, Geochemical and depth controls on microporosity and cavity development in the Maynardville Limestone: Implications for groundwater," Cave and Karst Science, v. 24, no. 3, p. 127–136." Comment submitted by Sidney W. Jones and Gareth J. Davies. Reply published in Forum, Cave and Karst Science, v. 25, no.3, p. 146–147.

Theses

Powers, J.G., 1998. Determination of formation transmissivity and specific yields through well hydrograph analysis at three, shallow, fractured and karstic sites. University of Nevada, Reno, MS thesis, 248 p.

Abstracts

Shevenell, L., and Powers, J.G., 2000, Transmissivity estimates from well hydrographs in multiple porosity aquifers. 31st International Geological Congress, Rio de Janeiro, Brazil, August 6–17, 2000.

Shevenell, L., 1999, Estimation of matrix transmissivity and variable specific yields in heterogeneous, multiple porosity aquifers using well hydrographs. Geological Society of America Abstracts with Programs, v. 32, no. 7, p. A-148.

Powers, J.G., and Shevenell, L., 1998, Determination of transmissivity and specific yields of a karst aquifer from monitoring well hydrographs. Transactions American Geophysical Union, EOS v. 79, no. 17, p. S153.

Shevenell, L., and Goldstrand, P.M., 1998, Secondary micro- and macro-porosity development and distribution in a karst aquifer. National Ground Water Association Technical Education Session, Las Vegas, NV, December 14–16.

Goldstrand, P.M., and Shevenell, L., 1997. Geologic controls on porosity development in the Maynardville Limestone, Oak Ridge, Tennessee. Geomechanics Abstracts, Issue 4, p. 221.

Contract Reports and Unpublished Reports

Powers, J.G., and Shevenell, L., 1999, Transmissivity Estimates from Well Hydrographs in Karst Aquifers. Y-12 Plant Report Y/TS-1775.

Shevenell, L., 1999, 1998 Progress Report: Use of well hydrographs in shallow fractured aquifers to determine specific yields and continuum transmissivities. Submitted to the U.S. Army Research Office, 3 p.

Shevenell, L., 1999, Review of use of well hydrographs in karst aquifers to estimate aquifer parameters: 1998 ARO Project Review. Submitted to the U.S. Army Research Office, Terrestrial Sciences Program Manager Dr. Russell S. Harmon, 6 p.

Shevenell, L., 1998, 1997 ARO Project Review: Review of use of well hydrographs in karst aquifers to estimate aquifer parameters. Submitted to the U.S. Army Research Office, Terrestrial Sciences Program Manager Dr. Russell S. Harmon, 6 p.

Shevenell, L., 1998, 1997 Progress Report: Use of well hydrographs in shallow fractured aquifers to determine specific yields and continuum transmissivities. Submitted to the U.S. Army Research Office, 5 p.

Shevenell, L., 1996, Use of well hydrographs in shallow fractured aquifers to determine specific yields and continuum transmissivities, Interim report. Submitted to the U.S. Army Research Office, 12/15/96, 4 p.

Presentations

Transmissivity estimates from well hydrographs in multiple porosity aquifers. 31st International Geological Congress, Rio de Janeiro, Brazil, August 6–17, 2000 (poster).

Use of well hydrographs to estimate aquifer parameters. DoD program review meeting, Boise State University, Boise, ID, June 22-24, 1999 (oral).

Estimation of matrix transmissivity and variable specific yields in heterogeneous, multiple porosity aquifers using well hydrographs. Geological Society of, Denver CO, October 25-28, 1999 (oral).

Determination of transmissivity and specific yields of a karst aquifer from monitoring well hydrographs. American Geophysical Union, Boston, MA, May 26-29, 1998 (poster).

Secondary micro- and macro-porosity development and distribution in a karst aquifer. National Ground Water Association Technical Education Session, Las Vegas, NV, December 14–16, 1998 (poster).

Use of well hydrographs to estimate aquifer parameters at karst and fractured sites. Army Research Office (DoD) program review meeting. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS, July 20-21, 1997 (oral).

7. List of Participating Scientific Personnel

Dr. Lisa Shevenell – Principal Investigator.

Mr. Jefferey Power was a fully funded M.S. student during this project and he earned an M.S. in Hydrogeology in 1998. His thesis title is "Determination of formation transmissivity and specific yields through well hydrograph analysis at three, shallow, fractured and karstic sites" (defended 9/24/98). Mr. Powers is currently employed by the U.S. Army Corps of Engineers, Baltimore District Office (P.O. Box 1715, Baltimore, MD 21203-1715).

Mr. Karl Neuman (M.S. student) and Mr. Timothy Hopkins (M.S. student) were paid on this project for a short period of time to begin compiling a database of all hydrograph data from the three sites investigated. This database was subsequently enhanced by Mr. Todd Umstot for use in his M.S. thesis work.

Mr. Todd Umstot is currently working toward an M.S. in Hydrogeology. The first year of salary and tuition for his thesis work on this project was paid by this ARO grant. He will complete his thesis in the coming year without any additional funding from ARO. Mr. Umstot's thesis topic is "Statistical analysis of well hydrograph responses in multiple porosity systems."

Mr. Ron Hess assisted with computer-related problems, training, and programming during various phases of this work and helped train Mr. Powers in GIS applications used in this project.

8. Report of Inventions

None

9. Bibliography

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Shevenell, L. 1996. Analysis of well hydrographs in a karst aquifer: Estimates of specific yields and continuum transmissivities. Journal of Hydrology, v. 174, no. 3/4, p. 331–356.

White, W.B. 1988. Geomorphology and Hydrology of Karst Terrains. Oxford University Press, New York: 464 pp.

10. Appendixes

Table 1. Summary of transmissivity values (m^2/d) computed with the hydrograph analysis method, slug tests, and pumping tests.

Well Number	Screen Depth (m)	Lithology/ Formation	Log Avail?	Zone Type Screen Int?	Useful Hyd Response?	# Storms for T estimates	Min T Value (m^2/d)	Max T Value (m^2/d)	Ave. T (m^2/d)	Standard Dev. T (m^2/d)	Slug Test T (m^2/d)	Pumping Test T (m^2/d)
Crane site												
03-06	11.4-14.2	BC LS	N	?	NA	0	--	--	--	--	7.3	--
03-24	12.8-15.7	BC LS	N	C	Y	10	0.4	3.1	1.1	0.8	a	--
03-31	na	BC SS	N	C?	N	7	--	--	--	--	57.4	--
03-32	na	BC SS	N	C?	Y	1	0.1	--	0.1	--	102.4	--
03-33	na	BC SS	N	C	N	7	--	--	--	--	134.8	--
03-34	na	BC SS	N	C?	Y	5	0.5	4.6	1.5	1.7	151	--
03-C11	14.5-17.5	BC LS	Y	M	NA	0	--	--	--	--	9.7	--
03-C5	9.8-12.8	BC LS	Y	C	NA	0	--	--	--	--	0.7	--
03C02	36.4-39.5	BB LS	Y	C	N	8	--	--	--	--	--	--
03C02P2	11.6-14.6	BC LS	N	C	Y	5	6.5	22.8	14.3	6.8	--	--
03C24	6.7-8.2	BC LS	Y	C	Y	2	1.0	1.4	1.2	0.3	11.6	--
Average of 4 nearby matrix wells (Murphy, 1995):												0.80
Fort Campbell site												
141mw1	18.3-21.3	clay/gravel	N	M	Y	2	0.62	0.67	0.65	0.036	--	--
141mw2	25.9-29.0	SL LS	N	F	Y	1	0.62	--	0.62	--	--	--
146mw1	37.8-40.9	SL LS	Y	M	Y	2	0.51	0.81	0.66	0.21	--	--
149mw1	10.7-13.7	silty clay	Y	M	Y	2	5.2	5.8	5.5	0.45	--	--
15m7e	25.2-28.3	SL LS	Y	C	NA	0	--	--	--	--	17.2	--
15mw3	13.1-16.2	silty clay	Y	C	Y	6	4.8	20.9	11.3	6.6	--	--
15mw5	26.8-29.9	SL LS	Y	C	Y	3	21.1	24.5	23.2	1.7	454.9	--
28mw11s	10.6-13.7	clayey gravel	Y	M	Y	3	8.6	55	26.9	24.8		--
2m5d	25.5-28.4	SL LS	Y	F/C	Y	4	0.074	0.13	0.092	0.023	0.1	0.09
2m8e	19.3-22.0	SL LS	Y	M	NA	0	--	--	--	--	0.2	--
2mw4	26.8-29.9	SL LS	Y	F	Y	2	0.077	0.09	0.084	0.0092	0.3	--
33m2e	10.5-13.6	SL LS	Y	C	NA	0	--	--	--	--	113.4	--
33m3e	9.6-12.6	SL LS	Y	C	NA	0	--	--	--	--	45.9	--
47mw2	4.6-7.6	SL LS	Y	C	N	5	--	--	--	--	27.2	--
47mw3	2.4-5.5	SL LS	Y	C	Y	1	0.008	--	0.008	--	580.6	--
5mw3	21.3-24.4	SL LS	Y	C	Y	4	0.39	0.51	0.47	0.051	30.9	--
5mw6	18.9-22.0	SL LS	Y	M	NA	0	--	--	--	--	19.4	--
6mw3	21.3-24.4	SL LS	Y	C	NA	0	--	--	--	--	2.4	--
7m3e	24.8-27.9	SL LS	Y	M	NA	0	--	--	--	--	0.01	--
9mw2	7.0-10.1	clay, LS	Y	C	Y	9	0.067	0.84	0.4	0.25	--	--
9mw4	11.6-14.6	SL LS	Y	F?	Y	4	0.088	0.47	0.22	0.17	--	--

Well Number		Lithology/ Formation	Log Avail?	Zone Type Screen Int?	Useful Hyd Response?	# Storms for T estimates	Min T Value	Max T Value	Ave. T	Standard Dev. T	Slug Test T	Pumping Test T
Oak Ridge site												
GW-052	4.1-5.6	Cmn	N	?	Y	5	11.5	40.4	25	12	--	--
GW-054	10.7-11.3	Cmn	core	?	Y	4*	6.1	47.4	18.5	19.6	--	--
GW-056	16.2-16.8	Cmn	core	?	Y	4*	1	5	3.6	1.8	--	2.1
GW-057	6.3-7.0	Cmn	core	?	Y	4*	0.8	6.3	4.5	2.6	--	1.3
GW-058	12.9-13.5	Cmn	core	?	Y	2	4	4.7	4.3	0.5	--	--
GW-059	7.0-7.6	Cmn	core	?	Y	7	1.6	5	3.4	6.4	--	--
GW-061	6.0-7.5	Cmn	core	?	Y	7	8.3	63	19	19.7	--	--
GW-167	7.9-9.2	Cmn	N	?	Y	1	25.9	--	25.9	--	--	--
GW-220	10.6-13.6	Cmn	N	?	Y	5	3.3	21	8.1	7.1	--	--
GW-225	45.7-61.0 (O)	Cmn	N	?	Y	2	7.8	9.6	4.1	1.2	--	--
GW-226	13.7-16.8 (O)	Cmn	N	M	Y	2	4.4	8.6	6.5	2.9	--	--
GW-603	19.8-22.9	Cmn	N	M	Y	2	10.1	10.1	10.1	0.01	--	7.6
GW-604	31.3-34.3	Cmn	N	M	Y	2	10.3	10.3	10.3	0.05	--	--
GW-621	7.6-12.3	Cmn	N	C	Y	7	0.9	7	3	2.1	--	--
GW-683	44.5-60.0	Ccr	Y	C	Y	2*	0.31	0.64	0.48	0.23	--	--
GW-684	34.7-39.1	Ccr/Cmn	Y	C	Y	2*	0.19	0.8	0.49	0.43	97.7	--
GW-685	27.0-42.2 (O)	Cmn	Y	F/C	Y	4*	0.91	5.9	3.2	2.1	--	4
GW-694	47.0-62.3 (O)	Cmn	Y	M	Y	2	1.6	3.3	2.4	1.2	--	--
GW-695	16.0-19.0	Ccr	Y	M	Y	3	3.2	4.2	3.7	0.5	--	--
GW-704	75.0-78.0 (O)	Cmn	Y	F	Y	3	2.1	2.9	2.6	0.4	--	--
GW-706	47.9-55.6 (O)	Cmn	Y	F	Y	1	2.8	--	2.8	--	--	--
GW-714	35.1-44.2 (O)	Cmn	Y	M	Y	1	8.7	--	8.7	--	--	6.9
GW-715	10.1-13.1	Cmn	Y	C	Y	7*	5.1	33.3	21.5	14.6	--	0.4
GW-728	90.2-93.1 (O)	Cmn	Y	C	Y	3*	2.8	7.9	5.7	2.6	--	--
GW-734	18.1-31.4 (O)	Cmn	Y	C	Y	4*	9.4	37.4	22.3	14.6	50.8	--
GW-735	20.7-23.8	Cmn	Y	C	Y	2*	26.8	40.1	33	9	--	0.3
GW-736	28.2-31.3	Cmn	Y	F	Y	1	2.8	--	2.8	--	--	--
GW-737	24.2-27.3	Cmn	Y	F/C	Y	2	4.8	7.5	6.2	2	--	--
GW-738	20.5-26.7	Cmn	Y	F/C	Y	3	0.41	2.4	1.4	1	--	--
GW-748	5.2-8.2	Cmr	Y	M	Y	2	8.1	10	9	1.3	--	--
GW-750	19.0-22.1	Cmn	Y	M	N	4	--	--	--	--	--	6.8
Average of 5 nearby matrix wells:											0.8	

The number of storms listed (# Storms) for wells with useful hydrographs is only the number with hydrographs that were analyzed. In most cases, other storms could not be analyzed (i.e., incomplete recessions, etc.). For those without useful hydrographs, this number is the total number of storms that occurred during the monitoring period.

Lithology/Formation: BC LS - Beech Creek Limestone; BC SS - Big Clifty Sandstone; BB LS - Beaver Bend Limestone; SL LS - St. Louis Limestone; Ccr - Copper Ridge Dolomite; Cmn - Maynardville Limestone; Cmr - Maryville Limestone.
Zone Type: M - matrix, F - fracture, C - cavity.
a this well recovered very rapidly (1 to 2 seconds) and the data could not be analyzed.
* The hydrograph T analyses omitted hydrographs with double peaks.

Table 2. Comparison of transmissivities estimated by different methods for individual wells at the three sites.

Well	Total Depth (m)	Zone Type	Average Hydrograph T (m^2/d)	Pumping T (m^2/d)	Average Slug T (m^2/d)
Crane site					
03-32	13.7	C?	0.1		102
03-34	15.2	C?	1.5		151
03c24	8.6	C	1.2		11.6
Average of 4 nearby matrix wells (Murphy, 1995):				0.8	
Fort Campbell site					
2m5d	28.6	F	0.09	0.09	0.1
2mw4	29.9	F/C	0.08		0.3
5mw3	24.4	C	0.47		31
15mw5	30.3	C	23		455
47mw3	6.1	C	0.008		581
Oak Ridge site					
GW-056	16.8	?	3.6	2.1	
GW-057	7.6	?	4.5	1.3	
GW-603	22.9	M	10.1	7.6	
GW-684	39.5	C	0.5	0.6	97.7
GW-685	42.2	F/C	3.2	4.0	
GW-714	44.2	M	8.7	6.9	
GW-715	13.6	C	21.5	0.4	
GW-734	31.4	C	22.4	5.4	50.8
GW-735	25.3	C	33.0	0.3	
Average of 5 nearby matrix wells:					0.8

Zone Type: M - matrix, F - fracture, C - cavity.

Table 3. Summary of computed transmissivities estimated by different methods at the three sites.

	Average Matrix T (m^2/d) Slug Test	Pumping Test	Hydrograph Analysis	Average Slug Test T (m^2/d) in Cavities
Crane site	8.4	0.8[1]	1.2	32 ± 63
Number of wells tested	2	4	5	6
Total number of tests	16	4	45	54
Ft. Campbell site	0.3	0.1	0.8	51 ± 226
Number of wells tested	4	1	13	9
Total number of tests	24	1	48	50
Oak Ridge site	1.1[2]	2.2	5.6	70 ± 33
Number of wells tested	5	8	31	2
Total number of tests	30	8	64	5

Averages are geometric mean T values computed for all wells in the particular category (slug, pumping, hydrograph). The total number of wells tested for each type of test (e.g., slug) is listed on the first line following the geometric mean T value. The total number of the particular test (e.g., slug) conducted at all wells tested is listed on the second line following the T value.

[1] Summarized from Murphy, 1995.

[2] Summarized from Jones, 1997, unpublished data, and Shevenell (unpublished data).